Undersea Laser Communication with Narrow Beams

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Abstract

Laser sources enable highly efficient optical communications links due to their ability to be focused into very directive beam profiles. Recent atmospheric and space optical links have demonstrated robust laser communications links at high rate with techniques that are applicable to the undersea environment. These techniques contrast to the broad-angle beams utilized in most reported demonstrations of undersea optical communications, which have employed light-emitting diode (LED)-based transmitters. While the scattering in natural waters will cause the beam to broaden, a narrowly directive transmitter can still significantly increase the optical power delivered to a remote undersea terminal. Using Monte Carlo analysis of the undersea scattering environment, we show the two main advantages of narrow-beam optical communication: increased power throughput and decreased temporal spread. Based on information theoretic arguments, gigabit-per-second class links can be achieved at 20 extinction lengths by utilizing pulse position modulation, single-photon-sensitive receivers, and modern forward error correction techniques.

Introduction

Undersea wireless communications is a significant challenge due to the highly attenuating nature of seawater for most electromagnetic frequencies. While acoustic communications has been demonstrated over long propagation distances (e.g., 1-10 km), it is limited to sub-megabit-per-second (Mbps) data rates, can suffer severe multi-path, and introduces orders of magnitude greater latency than optical signaling. By contrast, with blue-green optical communications, gigabit-per-second (Gbps) rates can be achieved, over distances potentially up to hundreds of meters in the clearest waters, enabling a host of new applications. Laser light can be collimated into extremely narrow beams, with sub-milliradian-class diffraction-limited divergence angles. Even in seawater, despite significant scattering, narrow transmitted beams yield an advantage by maximizing the power delivered to a remote terminal, provided the two terminals can point to each other with sufficient accuracy. In this paper, we explore the potential benefits as well as the challenges for undersea wireless communication with narrow optical beams.

The undersea systems analysis herein is inspired by lessons learned in the last few decades developing high performance laser communications (lasercom) for atmospheric and space applications. The recent Lunar Laser Communications Demonstration (LLCD) [1] achieved error-free communications from a moon-orbiting satellite to the Earth's surface at rates up to 622 Mbps. Both the space terminal (10-cm aperture transmitting 0.5 W of optical power) and ground terminal (array of four 40-cm receive apertures) were modest in terms of aperture and optical power. Another highly successful atmospheric lasercom demonstration was the Free-Space Optical Communication Airborne Link (FOCAL), achieving error-free 100-GB file transfers over 25+ km from an aircraft to a ground terminal at a rate of 2500 Mbps, with robust tracking out to 60 km [2]. Again, the optical power (0.5 W) and aperture sizes (2.5-

cm on the airplane, four 1.2-cm apertures on the ground) were very modest. Neither system required the complexity of adaptive optics.

LLCD and FOCAL provide lessons in optical communications applicable to undersea. Both systems used diffraction-limited beams to maximize power delivery. Each terminal tracked light transmitted from the remote terminal in a cooperative means for accomplishing pointing, acquisition, and tracking (PAT). The PAT systems were robust amidst platform vibrations and through the turbulent atmosphere. Due to the extremely long range, LLCD approached lasercom from the perspective of fundamental performance bounds. Two vital ingredients were a careful channel characterization and the information capacity analysis of the modulator/receiver pairs. In addition, LLCD demonstrated the operational utility of single-photon-sensitive detectors.

In this work, we explore the similarities and differences of the atmospheric and undersea channels, the technologies available for undersea, and the applicability of nuanced atmospheric PAT techniques. The paper is organized as follows: we begin with a description of undersea channel modeling, follow with a discussion of the benefits of narrow-beam optical systems, and conclude with implementation considerations.

Undersea Channel Characterization

Successful undersea lasercom will require a system design informed by a robust and accurate characterization of the propagation channel. This will especially be true with narrow-beam communications that seeks to push performance to the frontiers of what is physically realizable. Fortunately, ocean engineers have extensively worked to characterize the propagation of light through various seawater conditions. We rely on these characterization efforts and interpret them in the context of narrow-beam optical communication.

Signal attenuation due to absorption and scattering is, by far, the dominant loss term in any undersea optical communication link. While the scale of attenuation varies dramatically depending on the water characteristics, all undersea propagation is characterized by a loss exponential with propagation distance. The standard method for describing this loss is in terms of an absorption coefficient (typically given as a) and a scattering coefficient (given as b) both in units of m^{-1}. A beam attenuation length, or extinction length, of $(a+b)^{-1}$ m refers to the propagation distance that results in a power reduced by a factor of $e^{-1} \approx 0.37$ due to absorption and scattering. Alternatively, a scattering length of b^{-1} m refers to a reduction of e^{-1} due to scattering alone. Thus, small values of a and b denote clear water which allow light to propagate for longer distances. Typically referenced values are listed in Table 1. Higher scattering coefficients correspond to waters with higher concentrations of biomaterial, e.g., phytoplankton or chromophoric dissolved organic matter (CDOM), or in some cases suspended sediment. We can see a variation in extinction greater than a factor of 10; we also see that even in clear ocean conditions the exponential extinction is significant.

Table 1. Representative absorption and scattering coefficients at wavelength of 514 nm, taken from Petzold (1972) [3].

	Absorption Coefficient a (m^{-1})	Scattering Coefficient b (m^{-1})	Extinction Length $(a+b)^{-1}$ (m)
Clear Ocean	0.114	0.037	6.6
Coastal Ocean	0.179	0.219	2.5
Turbid Harbor	0.366	1.824	0.46

Atmospheric and free-space link losses are typically dominated by a beam spreading term proportional to R^{-2}, where R is the propagation range. For collimated beams of light undersea, the extinction loss $e^{-(a+b)R}$ dominates and the R^{-2} loss becomes nearly negligible in comparison. Note that this is only true for nearly collimated light; if the light source has a broad initial divergence angle, as with typical LED-based sources, then the R^{-2} loss plays a much more important role in the link budget calculations. In direct contrast to atmospheric lasercom, diffraction is almost irrelevant in terms of calculating link losses for undersea lasercom.

The most straightforward approximation of scattering effects, referenced above, is to treat all scattered photons as a link loss term. This "scattering as loss" approximation is highly appropriate for atmospheric lasercom links. However, in seawater, light is strongly forward-scattered, and some non-negligible fraction of the scattered light will in fact be collected by the receiver; a "scattering as loss" interpretation of the undersea channel is especially pessimistic for scenarios such as the turbid harbor where the scattering is substantially stronger than absorption. Inclusion of scattered light is vital to a correct comparison of wide-beam vs. narrow-beam optical systems.

Scattering also has a significant temporal effect on the optical waveform. Photons that scatter one or more times yet still reach the receive terminal have traveled a longer distance than "ballistic" photons that propagate without being scattered, resulting in a temporal spreading of the received waveform. Temporal spreading is a function of several system parameters, including the scattering coefficient, the propagation distance, the transmit beam size, the receive aperture size, and the receiver field of view (FOV). Intuition regarding the receiver FOV is particularly important for our narrow beam analysis: a narrow FOV receiver will limit the received photons to scattered light with very small scattering angles while a wide field of view will accept light that scattered significantly off axis. The former will have propagation distances very close to the ballistic photons, thus minimizing the temporal spread. Wide angle photons will have traveled longer distances and their inclusion makes the temporal spread more severe.

Modeling the channel response due to scattering is best performed by means of a ray-tracing, Monte Carlo simulation to compute the random paths of an ensemble of photons. Each photon is subject to a series of independent scattering events, with the frequency of such events characterized by the scattering coefficient b, and the resulting angle randomly drawn from a scattering phase function with a strong forward scattering emphasis. Given an initial distribution of photons constituting the lasercom beam exiting the transmit aperture, we compute the independent random walk for each

photon and approximate the distribution of photon density, arrival angle, and time of arrival at the receive aperture, using the invertible analytic volume scattering function (VSF) in Appendix B of [4]. An example photon density distribution is given in Figure 1. Despite the approximation's dismissal of coherence effects, such Monte Carlo ray tracing simulations are widely valued computational methods for modeling the undersea channel.

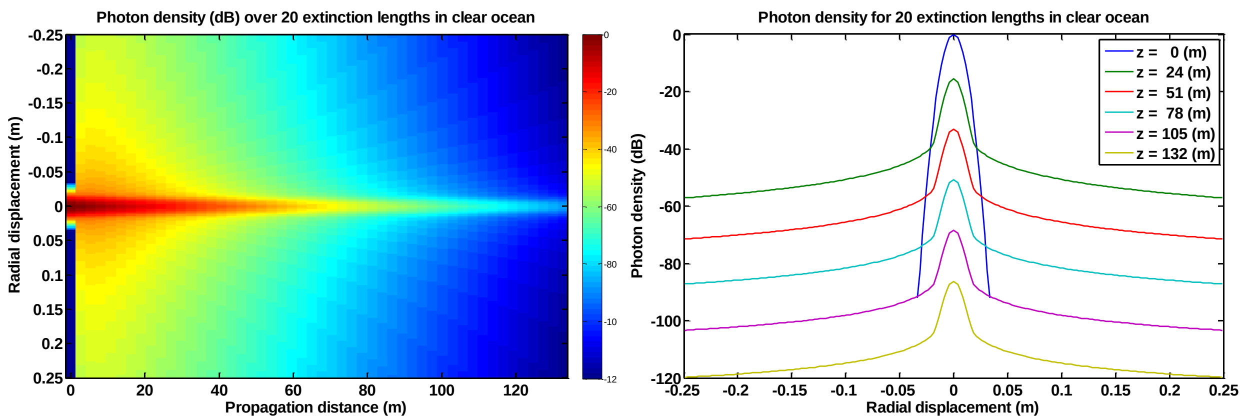

Figure 1. Simulated beam profile in clear ocean conditions. The transmit beam is Gaussian with a 1 cm radius beam-waist. The profile is given over distances up to 20 extinction lengths.

Benefits of Narrow-beam Lasercom

Narrow beam undersea lasercom has three significant advantages over wide beam optical communication: increasing the light transmitted across the channel, a reduction of the temporal spread of the signal, and enhanced spatial and spectral filtering options to reduce background light. To illustrate these impacts on communication performance, we begin with a discussion of modulation and information capacity in photon-starved channels. We follow with example scenarios in clear and turbid waters.

Modulation and Information Capacity for the Photon-starved Channel

The recent optical communication demonstration from the moon's orbit to an Earth ground station (the aforementioned LLCD) demonstrated high rate optical communication in what is sometimes referred to as the "photon-starved channel." Such a classification is given to a system where the total signal flux relative to the data rate is very limited. Deep space links (due to their astronomical distances) and undersea links (due to seawater's exponential extinction) can both exhibit photon-starved channels. While large apertures and high optical powers can partially compensate, practical size and power limitations encourage maximizing photon efficiency. In the case of LLCD, photon efficiency was increased by utilizing optical bandwidth (a plentiful resource) and detectors sensitive to single photons.

For the high rate LLCD downlink, multiple bits of information were communicated for every received photon. LLCD used a high bandwidth (5 GHz slot rate) signaling scheme utilizing 16-ary pulse position modulation (PPM) and half-rate forward error correction (FEC). For each 16 slot symbol, exactly one contained an optical pulse; the temporal location of the pulse-containing slot indicated which of 16 symbols was transmitted. The receiver deployed an array of single-photon detectors with precise time

of arrival resolution. By detecting the arrival of even a single photon per symbol, multiple bits of information were transmitted.

PPM signaling and single-photon receivers are directly applicable to the undersea environment. Information theory allows us to compute the best achievable efficiency with PPM and single-photon-sensitive receivers. Modeling the photon arrivals as Poisson distributed (characteristic of laser light) we calculate the channel capacity for PPM signaling in the ideal case of no background light. (For a detailed derivation of channel capacity for optical receivers, see [5].) Figure **2**a plots the achievable sensitivity versus the bandwidth expansion. A 16-ary PPM system with ½-rate FEC has a bandwidth expansion of 8 and can achieve -4.6 dB photons/bit, or 2.9 bits/photon. Figure **2**b shows the capacity of 16-ary PPM when N_b photons of background light, detector dark counts, and temporally spread signal photons are included. In a low-noise case such as a deep-water or night scenario, the sensitivity is close to the noiseless result. Higher background levels (e.g. from upward-looking, near-surface, daytime scenarios) impact the achievable sensitivity. Spatially and spectrally narrow filters increase the information capacity by reducing stray light to the detector.

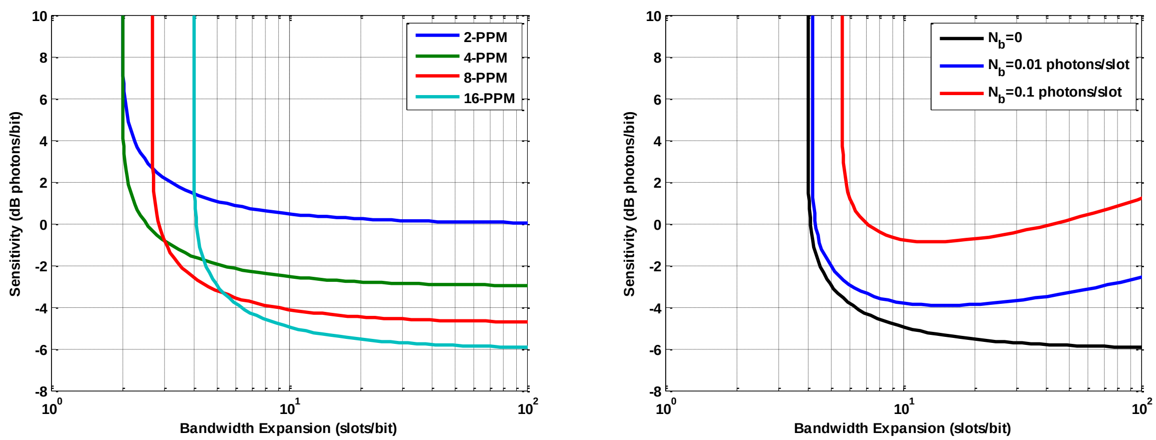

Figure 2. PPM sensitivity at capacity with ideal single-photon detecting receiver. In (a), PPM is compared for orders 2, 4, 8, and 16 with no noise photons included. In (b), 16-PPM sensitivity at capacity for noise levels of N_b=0.01 and 0.1 average photons per slot are compared to the noiseless case.

Clear Ocean Scenario – Increase Photon Delivery

Consider a clear ocean scenario with absorption and scattering coefficients of a=0.114 m^{-1} and b=0.037 m^{-1}, yielding an extinction length of 6.6 meters. A low size, low power, narrow-beam lasercom system can close the link over 20 extinction lengths (132 meters). Consider transmit and receive terminals with a 2 cm diameter and a collimated transmit beam at a wavelength of 515 nm. Even with such small terminals, 132 meters still represents near-field transmission, so in vacuum an aligned system would couple all of the light to the receiver. (We will assume that the terminals are properly pointed; discussion of methods for pointing and tracking follows in a later section.) The channel loss due to absorption and scattering is 87 dB, where we are assuming all scattered light is lost. For a 1 Gbps link using 16-ary PPM and ½-rate FEC, then we saw above that the noiseless sensitivity at capacity is 2.9

bits/photon. Such a system requires -109 dBW of received power. Even allowing 12 dB for imperfections (background light penalty, optics losses, FEC losses, pointing losses, non-unity detection efficiency, etc.), the narrow beam system could close the 1-Gbps link with 100 mW of transmit power.

For comparison purposes, we consider a wide-beam optical communication system (with the same aperture sizes) in which the transmitter illuminates an entire hemisphere (2π steradians) and the receiver similarly has a hemispherical field of view. The coupling into a 2 cm aperture incurs a substantial loss, partially mitigated by the fact that scattered light also couples to the aperture. 132 meters of propagation leads to a loss of 153 dB. By implementing a narrow beam system, we can increase the coupled light by over six orders of magnitude. With the same 100 mW transmit power, the maximum data rate of a wide beam system at that distance is 3.5 kbps.

Turbid Harbor Scenario – Reduce Temporal Spread

In the second case study, we consider a turbid harbor scenario with absorption and scattering coefficients of a=0.366 m^{-1} and b=1.824 m^{-1}. We will assume the same 2 cm terminals. In these waters, 20 extinction lengths are a distance of only 9.1 meters. In contrast to the clear ocean, scattering contributes significantly more to extinction than absorption. Both the narrow-beam and the wide-beam cases must account for the arrival of scattered photons. In Monte Carlo simulation, the narrow-beam system observes a loss of 67 dB, while the wide-beam system sees 80 dB of loss. The narrow-beam advantage to throughput, while present, is not nearly as dramatic as for the clear ocean case.

The advantage for the narrow-beam system in the harbor case is more evident in the temporal spread of the photon arrival. As seen in Figure 3, the wide-beam system has a significant spread in the time of arrival of the received photons. This can be understood intuitively by noting that most arriving photons have scattered multiple times causing them to follow random trajectories. More than 10% of the received photons arrive 10 nanoseconds after the earliest arrivals; it requires 200 nanoseconds before 99% of the photons arrive. The temporal spread causes inter-symbol interference (ISI) unless the signaling rate is reduced. (For PPM, ISI has an effect equivalent to background photons.) In contrast, the delay spread is significantly reduced in the narrow-beam case. Here only 1% of the photons arrive 10 nanoseconds after the earliest photons. Furthermore, because this is a tracked system, the receiver can spatially filter the received photons by their angle of arrival. Even a modest filter, such as 0.1 radians, dramatically reduces the delay spread so that 99% of the photons arrive within 1 nsec, as shown in the figure. Of course, such a filter reduces the number of arriving photons as well, by 4 dB in this example. Narrow spatial filtering enables high throughput signaling in the presence of severe scattering.

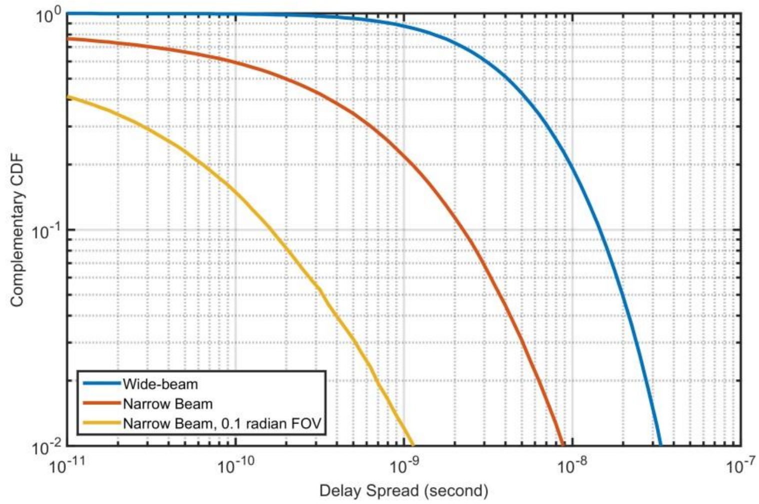

Figure 3. Temporal spread of photon arrivals in the turbid harbor case, from Monte Carlo simulation. The vertical axis is the complementary cumulative distribution function; thus 90% of photons arrive within 10 nanoseconds in the wide-beam case, 2 nanoseconds in the narrow-beam case, and 90 picoseconds in the narrow beam case with a 0.1 milliradian field of view (FOV).

Narrow-beam Lasercom Implementation Considerations

Communication System Dynamic Range

Tracked narrow beam optical systems are intended to achieve high data throughput at long distances. To accomplish their objective, the terminals would be designed for some specified low power level representing a desired number of extinction lengths. Water clarity, however, is variable over time. In addition, a robust system should be able to handle distances shorter than the maximum range. Either by shortening the propagation distance by a few extinction lengths, or by clarification of water, the communication link could find itself with orders of magnitude more optical power available. A robust system design would gracefully adjust to such power variations and be effective in a wide variety of undersea environments.

In the scenarios above, we cited 20 extinction length scenarios with throughputs ranging from -87 dB up to -67 dB for narrow beam systems in clear ocean and turbid harbor seawater, respectively. We've asserted the possibility for designing Gbps class communication systems under these circumstances. Such a receive terminal would certainly require sensitive optical detectors, which typically have dynamic ranges between 10 and 20 dB. A range reduction of 2-5 extinction lengths could move such a receiver into saturation, all other factors being equal.

The simplest mitigation method reduces the power coupled to the receiver. This could be done by transmit power reduction, transmit beam widening, or a receiver optical iris or other variable receiver attenuator. On the other hand, increased received signal strength is typically a boon to a communication system. The single-photon-sensitive receiver described above is applicable to the longest propagation range, but a higher bandwidth receiver uses the increased signal strength to

increase the data rate. A notional undersea lasercom terminal would have dual electro-optic front ends for the low signal and high signal cases.

Pointing, Acquisition, and Tracking

Initializing and maintaining a link between two lasercom terminals is often the most challenging aspect of a lasercom system due to their highly directive beams. Pointing, acquisition and tracking (PAT) are the three basic functions for a narrow-beam lasercom link. To begin, a transmitter terminal must know its position, its attitude, and the location of the receive terminal with sufficient accuracy to place light on the receiver. For terrestrial systems, location information may be derived from GPS and attitude information from an inertial navigation system. The transmitter typically sends a broader beam than will eventually be utilized and may scan across the predicted receiver location (known as the uncertainty region). Acquisition by the receive terminal is achieved when it detects light from the transmit terminal. Detectors used for acquisition typically cover a relatively wide FOV (milliradian-class). Tracking requires the receive terminal to adjust its own pointing solution such that it is aligned on-axis with the incoming beam from the transmit terminal. Lasercom systems typically employ a high-bandwidth control loop to null out disturbances on the receive platform and maintain the receive terminal on-axis pointing. In most lasercom systems, acquisition and tracking is employed at both the transmit and receive terminals in a bi-directional manner.

The PAT methodology described here can also be used to enable narrow beam undersea lasercom systems. A primary driver on PAT architecture for undersea systems is likely to be imprecise location information for the transmit and receive terminals. GPS connectivity will be intermittent (or unavailable) and navigation systems lose accuracy over time without a reference. The net effect will be that the uncertainty region that the transmit terminal is required to scan may be significantly larger than for typical atmospheric lasercom systems. Fortunately, the relatively slow (compared to aircraft or spacecraft) platform velocities for undersea platforms provide opportunities to accommodate increased acquisition times. An effective undersea lasercom PAT system design will trade transmit (or beacon) beamwidth, acquisition standoff range, and required acquisition time against anticipated open-loop pointing uncertainty to enable a practical PAT architecture for undersea lasercom systems.

Narrow-beam transmission underwater may be subject to brief, intermittent signal outages. These may occur due to tracking glitches (though such can be engineered to be rare) or due to marine organisms or detritus blocking the beam. A robust system should accommodate such outages by robust reacquisition and disruption-tolerant communication protocols (such as packet acknowledgment and retransmission).

Transmitter Technology

Much of the past work in undersea-undersea optical communications has exploited LED single device and multi-element array-based transmitters. These are commercially available in the low-attenuation undersea wavelength bands, are relatively low cost, and are capable of multi-Watt output. It is, however, difficult to drive LEDs with high extinction ratios at rates above ~10 MHz, and the low spatial coherence of LED transmitters make them hard to focus into narrow beams. Lasers, in contrast to

LEDs, are highly coherent, can have very small divergence angles, and can have narrow spectral linewidths.

Many commercially available semiconductor lasers in blue and green generate ~100 mW power levels and can be directly modulated at ~100 MHz rates. Some development may be required in the blue-green for faster signaling, either by direct laser modulation or external modulators. If additional power is required, a master-oscillator power amplifier (MOPA) architecture can be employed. While optical amplification is straightforward in the telecommunications wavelength bands and near 1 micron, there are few amplification options in the blue-green. However, amplification in combination with frequency conversion is feasible. For example, a 1060nm Yb laser can be followed by an external modulator, followed by an optical amplifier, and finally followed by a second-harmonic generation (SHG) crystal.

Optical amplification provides a valuable benefit for communications links with widely varying dynamic range. The output of optical amplifiers is average power limited. As the pulse repetition frequency is lowered, the energy per pulse increases, improving the receiver signal-to-noise ratio (SNR). Thus, the transmitter can be dynamically adapted to the varying loss of a particular link, e.g. as the terminals move towards or away from each other, or as the properties of the water change (e.g. increased phytoplankton concentration closer to the surface).

Receiver Filter Technology

Optical filtering enables the receiver to spectrally distinguish the signal of interest from out-of-band ambient light, a critical function for undersea receivers in shallow waters and daytime operations. An advantage of using narrow beams for communication between undersea terminals is that COTS interference filters can be used effectively, despite their incidence-angle-dependent passbands. This enables the designer to avoid the use of the specialized filters (Lyot, atomic line filter) required for wide FOV narrowband filtering.

Detection Technology

High sensitivity photon-counting detectors are highly desired in undersea optical communications systems. These detectors include photomultiplier tubes (PMT), microchannel plate (MCP) detectors, and avalanche photodiodes (APD).

PMTs have been the mainstay of undersea optical communications systems. They can be operated at reasonably high rates, enabling tens to hundreds of Mbps data rates. PMTs also tend to have large active areas, facilitating the collection of received light. They can be very sensitive, even to the point of counting single photons. They have quantum efficiency in the blue-green of up to a few tens of percent. PMTs can have some disadvantages as well, including noisiness, limited dynamic range and limited lifetime – particularly when operated at high count rates.

MCPs also utilize electron multiplication, with a large number of parallel photocathodes and channels (tubes or slots), each ~10 microns in diameter. MCPs can offer very good response times, and, being arrayed, can provide spatial resolution unlike a single pixel PMT. A disadvantage of most MCPs is

that they cannot thermally tolerate sustained current and therefore only support low count rates. As with PMTs, MCPs can be noisy and have lifetime limitations.

APDs are solid-state, semiconductor devices that do not suffer the secondary electron emission damage common to PMTs and MCPs. APDs can be operated in linear mode, typically for high-speed applications, or in Geiger mode (with extremely high gain) for single-photon-sensitivity [6]. Silicon APDs can be designed for efficient operation in the blue-green and also offer relatively low multiplication noise. They can operate at rates of tens to hundreds of MHz in Geiger mode, and GHz rates in linear mode. APDs typically have much smaller area than PMTs, but can be arrayed, enabling spatial resolution. With proper readout circuit design, the arraying of Geiger mode APDs can be exploited to improve temporal performance as well [6]. Each APD pixel has a finite reset time, but if the readout circuit is designed such that each pixel can be re-armed after firing (rather than periodically re-arming the entire array) then the effective bandwidth of the array will scale with the number of pixels in the array. We have architected asynchronous readout circuits for this purpose, and with sufficient investment, the architecture should be scalable to Gigacount per second (Gcps) rates [7].

Conclusion

To illustrate the potential capacity gains achievable using narrow beams, we plot in Figure 4 predicted achievable capacity (in red) vs. performance reported by published demonstrations ([8], [9], [10], [11], and [12]). The predicted performance invokes PAT, sensitive detectors, photon-efficient modulation, and FEC as described in the paper. The terminal assumptions are modest, with 100 mW of transmit power and 2 cm apertures as discussed in the scenario examples. Theoretically, ~60 dB of sensitivity increase is possible at Gbps data rates (in the analysis, we arbitrarily imposed a 1 GHz signaling rate). Implementing a near-capacity system that approaches this previously unrealized undersea communications performance gain should be feasible using the systematic design methodologies described herein. Of course, cost-effective realization for widespread deployment would require further maturation and productization of some devices and subsystems.

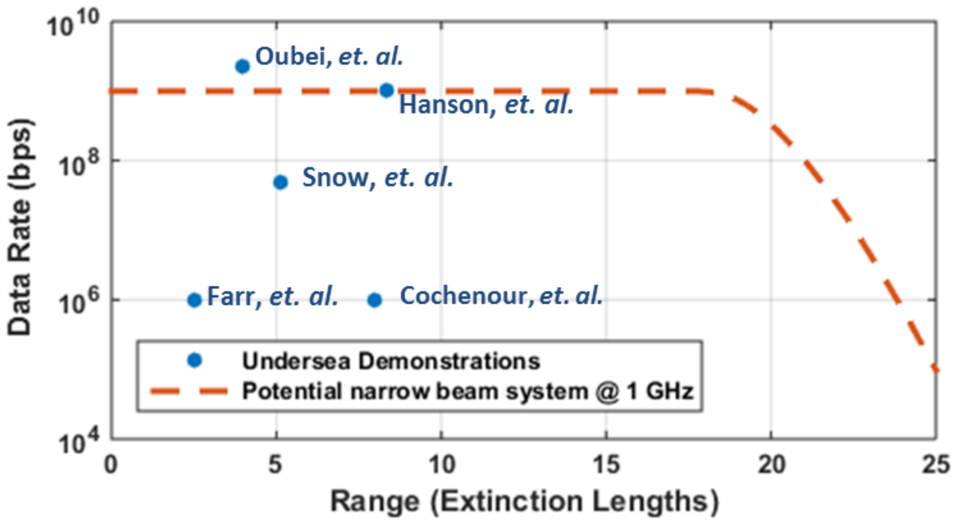

Figure 4. Fundamental channel capacity analysis for an undersea lasercom system employing a narrow-beam transmitter and a photon-counting receiver predicts significant performance gains are achievable compared to prior demonstrations. Assumed system operates at 1 GHz, with 2 cm transmit and receive apertures and 100 mW of transmit power. Range is plotted in beam attenuation lengths (extinction lengths).

Many previous undersea lasercom systems have been designed to operate with over-powered wide-beam optical power transmitters that fall short of optimal performance. We have outlined a path to achieving significant performance improvement for undersea lasercom links using narrow-beam actively-pointed transmitters and photon-counting receivers designed to operate with high-sensitivity waveforms and powerful error correction coding. This class of narrow beam undersea lasercom systems can also be extended to accommodate received photon flux that varies over an extremely large dynamic range for different seawater types or link distances. We believe that undersea lasercom systems designed using the methodology described in this paper will enable longer-range, higher-rate links using practical optical transmit powers for compatibility with a broad range of undersea platforms and application requirements.

Acknowledgement

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